



Identifying spatial clusters of flood exposure to support decision making in risk management



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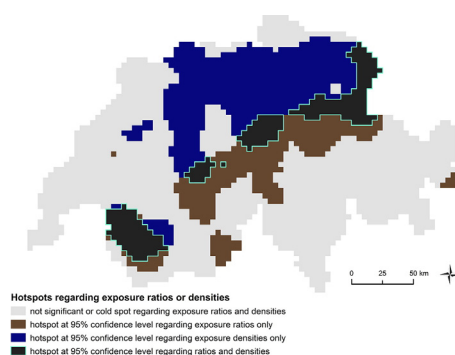
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HIGHLIGHTS

- Evaluation of methods and parameters pertinent to flood exposure analyses
- Spatial exposure analyses support prioritization in flood risk management.
- Feasible detection of hotspots at national scale based on spatially explicit data
- Complementary spatial distribution of exposure *densities* and *ratios* in Switzerland
- Data aggregation scheme (i.e. by municipalities or grids) influences the results.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:

Received 31 October 2016

Received in revised form 8 March 2017

Accepted 22 March 2017

Available online xxxx

Editor: R. Ludwig

Keywords:

Flood exposure
Flood risk management
Prioritization strategies
Spatial cluster analysis
MAUP
Switzerland

ABSTRACT

A sound understanding of flood risk drivers (hazard, exposure and vulnerability) is essential for the effective and efficient implementation of risk-reduction strategies. In this paper, we focus on 'exposure' and study the influence of different methods and parameters of flood exposure analyses in Switzerland. We consider two types of exposure indicators and two different spatial aggregation schemes: the density of exposed assets (exposed numbers per km²) and the ratios of exposed assets (share of exposed assets compared to total amount of assets in a specific region) per municipality and per grid cells of similar size as the municipalities. While identifying high densities of exposed assets highlights priority areas for cost-efficient strategies, high exposure ratios can suggest areas of interest for strategies focused on the most vulnerable regions, i.e. regions with a low capacity to cope with a disaster. In Switzerland, the spatial distribution of high exposure densities and exposure ratios tend to be complementary. With regards to the methods, we find that the spatial cluster analysis provides more information for the prioritization of flood protection measures than 'simple' maps of spatially aggregated data represented in quantiles. In addition, our study shows that the data aggregation scheme influences the results. It suggests that the aggregation based on grid cells supports the comparability of different regions better than aggregation based on municipalities and is, thus, more appropriate for nationwide analyses.

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1. Introduction

Flood risk has been increasing during the last decades on a global scale (IPCC, 2012); this is exemplified by the occurrence of flood events associated with high losses in Europe (e.g. 2002 Danube, Elbe and Vltava catchments, 2007 United Kingdom, 2014 Southeast Europe, 2016 Northwest Europe). The flood events prompted political actions with a focus on the generation of flood risk maps and enhanced national risk management strategies, e.g. the [European Parliament's Floods Directive \(2007\)](#) or the respective frameworks in Switzerland ([Bründl et al., 2009](#); [PLANAT, 2005](#)). Flood risk analysis combines information about the hazard (i.e. the frequency and magnitude of floods), exposure (i.e. the population and assets located in flood-prone areas) and vulnerability (i.e. the susceptibility of the exposed elements to the hazard) ([Klijn et al., 2015](#); [Merz and Thieken, 2004](#); [Papathoma-Köhle et al., 2011](#); [UNISDR, 2015a](#)). These three main factors of the risk analysis show spatiotemporal patterns ([Aubrecht et al., 2013](#); [Black and Burns, 2002](#); [Fuchs et al., 2013](#); [Mazzorana et al., 2012](#); [Winsemius et al., 2016](#)). In particular, several studies and reports identify increasing in exposure as the main driver of increasing risk ([Hallegatte et al., 2013](#); [IPCC, 2012](#); [de Moel et al., 2011](#)). In the future, flood risk will continue to increase because of socio-economic development and climate change ([Visser et al., 2014](#); [Winsemius et al., 2015](#)). Consequently, effective and efficient strategies for risk reduction are essential for the future ([Jongman et al., 2014](#); [Rojas et al., 2013](#)) and a sound understanding of relevant risk drivers is a prerequisite for the implementation of risk-reduction strategies ([IPCC, 2012](#); [UNISDR, 2015b](#)).

In this paper, we focus on exposure and how the associated data analysis can influence decisions in different risk-based strategies. Exposure analysis is strongly dependent on availability, resolution and quality of data, namely data on assets (i.e. including affected people, buildings and infrastructure) and on the nature of the hazards (i.e. flood extent and magnitude). Asset data characteristics, in particular the spatial resolution and the aggregation level, also influence the choice of methods for exposure analysis. Examples of exposure analysis approaches include intersecting flood areas with average asset values based on aggregated land-use classification (e.g. [Cammerer et al., 2013](#); [Jonkman et al., 2008](#); [Muis et al., 2015](#)) and spatially explicit intersections of building polygons ([Figueiredo and Martina, 2016](#); [Fuchs et al., 2015](#)). The latter approach generates high quality and spatially explicit information on exposure, thereby reducing uncertainties if up-scaled to a larger spatial entity. [Merz \(2006\)](#) compares different exposure analysis approaches and [de Moel et al. \(2015\)](#) provide an overview concerning spatial scales. Additionally, the levels at which exposed assets are aggregated are dependent on data privacy restrictions, data availability and study objectives. Aggregation levels can range from municipality level ([Fuchs et al., 2015](#); [Hallegatte et al., 2013](#); [Huttenlau et al., 2010](#); [Staffler et al., 2008](#)) to NUTS levels for European studies ([Lugeri et al., 2010](#); [Lung et al., 2013](#)) and aggregation based on countries (and 'food producing units') for global studies ([Jongman et al., 2012](#); [UNISDR, 2015a](#)). However, due to limited data availability, comprehensive object-based and therefore spatially explicit analyses are generally restricted to local and regional levels ([Huttenlau et al., 2010](#); [Zischg et al., 2013](#)). Since additional information has become increasingly available (e.g. on building stock, i.e. existing buildings within a defined environment) throughout Europe based on new European regulations, more accurate information on exposed elements can be obtained (e.g. [Figueiredo and Martina, 2016](#); [Fuchs et al., 2015](#)) and will be used as a basis for decision-making in risk management.

In Switzerland, object-specific information about the building stock and flood hazards map are available nationwide. In this study, we investigate and test the application of different aggregation and normalization methods on these datasets and highlight their impact on resultant differences to build awareness among relevant decision makers. The legislative framework and the limited funds for protection measures oblige authorities to prioritize the most efficient and effective risk

reduction schemes. Thus, decision makers need to know "which region should risk reduction focus on?" or alternatively, "where are the flood exposure hotspots located?". To answer these questions, we propose an approach of spatial cluster analysis based on the aggregation of point data with respect to different spatial units. Spatial cluster analyses are well established in many disciplines (crime, health, archeology, with [Snow's \(1855\)](#) publication on the 1854 cholera outbreak in Soho district of London being to our knowledge the first work on spatial clusters), but with limited applications in natural risk analysis and management to date. The few studies on natural hazards that apply spatial cluster analyses (e.g. [Borden and Cutter, 2008](#); [Fuchs et al., 2012](#); [Kazakis et al., 2015](#); [Su et al., 2011](#); [van der Veen and Logtmeijer, 2005](#)) often use aggregated data and rarely consider the influence of the shape and size of the data aggregation units. In our study, we investigate if and to what extent the aggregation scheme influences the results. In other words, we examine the relevance of the still unresolved and thus often ignored Modifiable Areal Unit Problem (MAUP) ([Openshaw, 1984](#); cf. also [Section 2.4](#) in this paper).

We further consider two types of exposure indicators: the density of exposed assets (exposed number of assets per km²) and the share of exposed assets (share of exposed assets compared to the total number of assets in a specific region). The first indicator, the exposure density, supports risk management strategies that follow the concept of utilitarianism ([Mill, 2007](#)). Utilitarianism in natural hazard and risk management means to choose the most cost-efficient measures. Numerous factors influence a measure's efficiency, i.e. the ratio of resource input to the risk reduction output. The density of exposed assets is an example of the aforementioned factors. Provided that all factors are the same except the exposure density, the efficiency of a measure is higher in areas with high densities of exposed assets than in areas with low exposure densities. That is, the density of exposed assets is a meaningful criterion for the selection of measures with respect to cost efficiency. The second exposure indicator, the share of exposed assets, informs strategies which comply with Rawls' concept of justice ([Rawls, 1971](#)). The application of this concept in risk management implies the prioritization of the most vulnerable areas and people ([Johnson et al., 2007](#)). The term 'vulnerable' in this context does not refer to the individual physical susceptibility of assets in a region, but to the missing capacity of a region to cope with a disaster. We assume an inverse relationship between the share of affected assets and a region's coping capacity. Consequently, we propose that the share of exposed assets in a given spatial unit is used as an indicator of the unit's vulnerability.

The proposed approach of spatial cluster analysis is generally applicable, i.e. for different regional and national flood exposure surveys. In this paper it is applied and illustrated with the case study of Switzerland.

2. Material and methods

For the analysis of flood exposure, we overlay spatially explicit information about buildings and inhabitants with data describing flood prone areas. Based on different aggregations of the exposed assets we search for statistically significant hotspots of flood exposure. The following sections outline the methods applied and describe the datasets used in the Switzerland case study.

2.1. Data on buildings and inhabitants

Two datasets are extracted from (1) a topographic landscape model and (2) from point data on residential buildings and combined to obtain a comprehensive and homogenous, country-wide database of buildings polygons and of residents in Switzerland.

The feature group 'buildings' from the 'Topographic Landscape Model' (TLM) ([swisstopo, 2016a, 2016b](#)) contains footprints of all buildings currently in Switzerland. The TLM building data is highly accurate (10⁻¹ m), however, the spatial subsets of the data are not updated

simultaneously, but regionally in phases between the years 2009–2015. In addition, the change of the building data from 2D to 3D representation is completed only for approximately half of the area (swisstopo, 2016c). Consequently, there are regional differences, e.g. in the degree of division and overlaps of building polygons and the date of underlying aerial images. We address the shortcoming regarding the spatially different stages of 2D to 3D conversion by merging all adjoining or overlapping building polygons, so that terraced houses or apartment blocks are homogeneously represented as one single polygon. Furthermore, we correct invalid geometries. After these preprocessing steps, our dataset includes 2,086,411 non-overlapping building polygons with a total areal footprint of 540 km².

The federal 'Buildings and Dwellings statistic' (Gebäude- und Wohnungsstatistik (GWS)) contains point-referenced data of all buildings (entrances) for residential use in Switzerland (Federal Statistical Office FSO, 2016). The number of inhabitants (main residence) at the end of 2012 is used in our study. The dataset contains 1,670,054 points with slightly over 8 million (8,057,480) inhabitants assigned to them.

We assign the number of inhabitants to the building footprints by intersecting the GWS point data with building footprint polygons and applying a snapping distance of ≤ 2 m. Within this distance, 97.7% of all points in the GWS can be attributed to a neighboring building polygon. For the total number of inhabitants per building, we total the number of inhabitants of all points associated to a specific building polygon.

2.2. Flood maps

We combine two different types of flood maps to define the areas potentially prone to inundation. The main source of data is a compilation of all available communal flood hazard maps, which are complemented by a nationwide floodplain model called 'Aquaprotect'.

The communal flood hazard maps are generated at the local municipal or cantonal level with respect to Swiss national guidelines (Borger, 1999; Loat and Petrascheck, 1997) and include information from historical events, 2D flood simulations and expert knowledge. Within the perimeter of the communal flood hazard maps, five different hazard classes ('high', 'medium', 'low', 'residual' and 'no or negligible') are defined by a specific combination of intensity and probability of events. The communal flood hazard maps are widely accepted and used, especially in the planning process of flood protection measures at communal and cantonal levels (Bundesamt für Umwelt BAFU, 2016a). In our study, we use the March 2016 versions available from the 26 Swiss cantons (federal states) and consider the hazard classes 'high', 'medium' and 'low' as flood prone areas (i.e. we include areas affected by events up to a return period of 300 years).

67% (1,390,382) of the building polygons (70% of footprint areas, 77% of residents) are located within the perimeters of the communal flood hazard maps. For the buildings located partially or completely outside of these perimeters (i.e. buildings without flood assessment at the local level), the Aquaprotect dataset provided by the Federal Office for the Environment (Federal Office for the Environment, 2008) is used complementarily. This dataset defines inundation areas based on a "geomorphologic regression" approach (Feyen et al., 2003); this approach has been applied in Switzerland on a 25 m \times 25 m grid. Technical flood control facilities and catchment areas below 10 km² are not considered by Aquaprotect (Federal Office for the Environment, 2008). Aquaprotect includes four different layers with recurrence periods of 50, 100, 250 and 500 years. We use the layer with the 250 year return period in addition to the communal flood hazard map's areas of events with a return period of up to 300 years.

2.3. Exposure analysis

The two datasets – of building footprints and of flood prone areas – are spatially intersected within a GIS to assess the flood exposure of buildings and residents. A building (and its inhabitants) is classified as

exposed if the (partial or whole) footprint polygon overlaps with a flood prone area according to the communal flood hazard maps (classes 'high', 'medium' and or 'low'). If the building footprint is located outside of the perimeter (i.e. it is without flood assessment at the local level), it is exposed if it overlaps with the considered Aquaprotect layer. Buildings that are located on the fringes of the perimeter of the communal flood hazard maps (i.e. partially inside and outside the perimeter) are classified as exposed if they overlap with one of the three considered classes of the flood hazard maps and/or with the respective Aquaprotect layer.

2.4. Spatial aggregation of data and density calculation

We aggregate the number of exposed buildings, associated footprint and inhabitants based on the currently defined Swiss municipal districts. The values are then normalized by the area of the respective polygon to determine the resultant densities of exposed assets. The Swiss municipalities dataset (swisstopo, 2016d) consists of 2312 entities, covering the entire national territory of 41,290 km². 2294 of these entities are actually territories of municipalities, 16 are cantonal territories (coinciding mainly with lake areas) and two are 'communanzas' or public areas managed communally by farmers. The sizes of the 2312 polygons range from 0.1 km² to 439 km² with a mean value of 18 km². With reference to motivation stated in the introduction, we are interested in investigating whether data aggregation by municipal districts influences data analysis results. That is, we want to determine if the 'Modifiable Areal Unit Problem' (MAUP) impacts the analysis of flood exposure of Swiss municipalities. The MAUP includes two aspects, (1) the scaling and (2) the zonation effect (Openshaw, 1984; cf. also Charlton, 2008). The scaling effect describes the observation that analytical results change based on the level of data aggregation (e.g. block census vs municipal districts vs county level). The zonation effect describes inconsistencies in results when the number of areal units (and thus their average size) remains constant, while boundary positions are shifted. In our study, we focus on the zonation effect by creating an arbitrary grid of 4.23 km \times 4.23 km cells, covering the entire Swiss territory. The comparison of the results based on these grid cells (2533 cells, each 17.8929 km²) with the results based on aggregation by municipalities (2312 polygons with an areal average of 17.8592 km²) supports the assessment of how relevant the MAUP zonation effect is. To calculate the densities of exposed buildings, footprint areas and inhabitants in each grid cell, we apply the quadratic kernel function described by Silverman (1986) with a window 6.345 km wide.

We apply the same density calculation procedures to the total building stock (exposed and unexposed buildings) and divide the densities of exposed buildings by the densities of the total building stock. We obtain relative exposure ratios of building numbers, footprint areas and inhabitants per municipality and per grid cell, respectively.

To determine the robustness of the results based on grid cells we shift the arbitrarily set grid by half of its cell width in each direction, i.e. by 2115 m in north-south and east-west respectively, and repeat the described density calculations. The resulting densities and their distributions within this second grid are very similar to ones in the first grid. Thus, we proceed solely with the first grid.

2.5. Detection of spatial clusters

'Hotspots' and 'spatial clusters' are defined differently and many relevant techniques can be applied to detect these spatial patterns (see Getis, 2008 for a historical outline, and Legendre and Legendre, 2012 for a topical overview and mathematical details). From the available range of interpretations, Levine's definition of a hotspot as an "extreme form of spatial autocorrelation" (Levine, 2008) and Knox's definition of spatial clusters as "geographically ... bounded group[s] of occurrences ... of sufficient size and concentration to be unlikely to have occurred by chance" (Knox, 1989) are of particular interest.

We apply the local spatial autocorrelation statistic $G_i^*(d)$, by Getis and Ord (Getis and Ord, 1992; Ord and Getis, 1995), to identify hotspots of flood exposure in Switzerland. In other words, the aim is to detect statistically significant clusters of high values in terms of densities of exposed buildings (numbers, footprint areas and inhabitant), as well as in terms of relative exposure ratios. The confidence level is set at 95%, and for d , we use fixed distance bands. We set the first distance band just above the maximal distance between centroids of neighbors (i.e. at 21 km for municipalities and at 4.25 km for grid cells) to assign to each municipality or grid cell at least one neighbor. We investigate the effect of the size of d by increasing it for municipalities to 31.5 km and 42 km and for grid cells to 8.5 km, 12.75 km, 17 km and 21.25 km.

The evaluation of the $G_i^*(d)$ statistical framework reveals additional issues with both spatial dependence and multiple testing. While the spatial dependence violates the test requirement of independent features, the multiple testing leads to a high number of false type I errors, i.e. incorrect rejections of the null hypothesis. Therefore, it is necessary to adjust the critical values of the G_i^* statistics. We use the method proposed by Caldas de Castro and Singer (2006).

3. Results and discussion

The data resulting from the assignment of point data on inhabitants (GWS dataset) to building footprints (TLM dataset) are presented in Section 3.1, together with the national level results from the flood exposure analysis. In Section 3.2, we discuss selected outcomes of the spatial aggregation investigation and of the density and ratio calculations. Section 3.3 describes the results of the spatial clusters analysis. The relevance of the MAUP is addressed in Section 3.4, and in Section 3.5, we discuss the implications of our findings for the prioritization of flood risk reduction measures. The annex presents supplementary results to the selected outcomes described in Section 3.2.

3.1. Exposed assets: buildings and residents

A total of 97.7% (1,631,531) of the GWS data points are assigned to a building footprint polygon (i.e. 93.7% are located within a TLM building footprint polygon and 4% within a distance of ≤ 2 m). These assigned GWS data points represent 98.2% (7,909,191) of the Swiss residents. The high percentage of residents assigned to buildings reflects the high spatial accuracy of both the GWS points and the TLM footprints datasets.

Overall, 320,509 buildings in Switzerland are identified as exposed to floods up to a return period of 250 to 300 years (see Table 1). This is equivalent to an exposure ratio of 15.4%. This ratio is in agreement with results from previous studies conducted with Switzerland as a study site (Bundesamt für Umwelt BAFU, 2016b; Fuchs et al., 2017) and is in line with findings about other mountainous regions in Europe (Chen et al., 2016; Fuchs et al., 2015; Url and Sinabell, 2008). The exposure ratios of the building footprint areas and of the number of residents are higher (20.4% and 17.1%, respectively) but still comparable to the ratio regarding the numbers of buildings. This indicates that the average footprint area of exposed buildings is greater than the average footprint area of unexposed buildings in Switzerland (343 m² for exposed versus 244 m² for unexposed, cf. Table 1). The same comparison is valid for the number of residents. However, the relative difference between the average number of inhabitants in exposed buildings (4.2 persons per

building) and in unexposed buildings (3.7 persons per building) is smaller. Fuchs et al. (2015) obtain similar findings with respect to larger buildings located inside of flood prone areas and explain that larger buildings require more flat terrain. Consequently, they are preferably built on floodplains. A second explanation for the higher exposure ratios associated with larger buildings is related to the applied method. It scores any building overlapping with flood prone areas as “exposed”, regardless of the percentage of the building footprint that intersects with the flood area feature. As a result, large building polygons are more likely to be scored as “exposed” than small ones.

The last column in Table 1 presents the exposed elements normalized by the total area of Switzerland (41,290 km²). An average of eight buildings (2,700 m² footprint area, 33 inhabitants) are exposed per square kilometer. These normalized figures are revisited in the following section, where we present the densities of exposed assets based on spatial aggregations with different spatial units.

3.2. Spatial aggregates, densities and ratios of exposed assets

Fig. 1 presents the aggregation of the number of exposed buildings per municipality normalized per square kilometer in five 20%-quantiles. The limit between the middle and the second highest class coincides with the average value of eight exposed buildings per square kilometer considering all of Switzerland (cf. Table 1). Consequently, 60% of the municipalities (the three lower classes) have densities that are less than or equal to the nationwide average. Furthermore, the mean of the density values of all municipalities is approximately 13 exposed buildings per square kilometer, which is >50% higher than the nationwide density. In other words, the density distribution per municipality is not symmetrical but right-skewed and small municipalities are generally associated with higher densities than large ones. Considering the spatial distribution of the densities, low values are generally concentrated in the south-eastern part of Switzerland. In contrast, many municipalities with high densities are located in the central and the northern parts of the country, with the exception of two lines of high values in the south (areas A and B in Fig. 1).

Fig. 2 also presents densities of the number of exposed buildings, but per 4.23 km \times 4.23 km grid cells. The thresholds used to define the five plotted classes are the same as in Fig. 1. Overall, the spatial distribution pattern of the densities per grid cell in Fig. 2 is similar to Fig. 1, but the high density values in area B (in Fig. 1) are less prominent. Here, the high values of some small municipalities ($\ll 18$ km²) are smoothed out when the densities are calculated per grid cell. This smoothing effect of high and low density values affects all regions, where the areas of municipalities are considerably smaller than the areas of the grid cells. Additionally, the applied kernel density estimation with a window width of 6.345 km smoothens the resultant values. However, this smoothing effect of the kernel density estimation is cancelled out in regions where the municipal areas are notably larger than the grid cell areas. Consequently, in regions with large municipalities, the variability of the underlying exposure data is more evident in the density maps organized per grid cell (e.g. area C in Fig. 2) than per municipality.

In principal, the exposure density in a particular spatial unit is the result of two underlying features, (1) the density of assets (number of buildings, footprints or inhabitants per square kilometer of this spatial unit) and (2) the proportion of flood prone area to the total area of this spatial unit. While the high exposure density in the northern part

Table 1
Flood exposure in Switzerland. Norm. = normalized per km², surface of Switzerland: 41,290 km².

Asset type	All	Not exposed	Exposed	Ratio [%]	Norm. [/10 ⁶ m ²]
	[N] or [10 ⁶ m ²]	[N] or [10 ⁶ m ²]	[N] or [10 ⁶ m ²]		
Number of buildings [N]	2,086,411	1,765,902	320,509	15.4	8
Footprint area of buildings [10 ⁶ m ²]	540	430	110	20.4	0.0027
Number of residents [N]	7,909,191	6,556,486	1,352,705	17.1	33

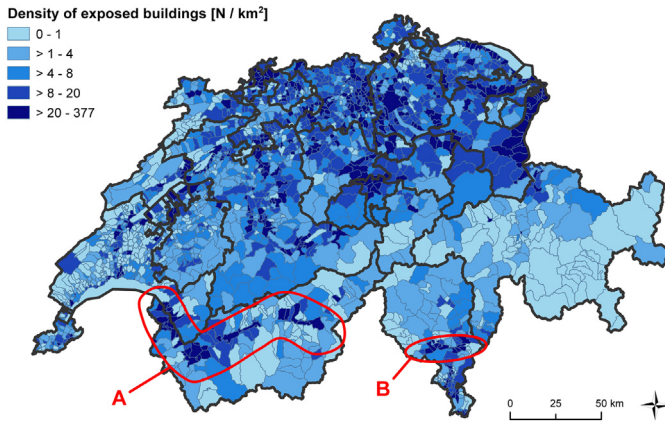


Fig. 1. Densities of flood exposed buildings per Swiss municipality, numbers per km². Data classes are (rounded) 20% quantiles. Fine lines represent municipal boundaries and thick lines represent cantonal boundaries. Areas A and B highlight two lines of high values in the south of Switzerland.

of Switzerland is attributed to an overall high density of assets in these lowlands and hilly regions, the high exposure densities in the mountainous south correspond with the high settlement concentrations located on the main alpine river floodplains that extend across the entire valley bottom (Zimmermann and Keiler, 2015).

The spatial distributions of the building exposure ratios per municipality are shown in Fig. 3, classified in five quantiles of 20%. The 15.4% nationwide exposure ratio (see Table 1), as well as the mean of the exposure ratios of all municipalities (13.9%) belong to the second highest class, indicating a right-skewed distribution. However, unlike the density values per municipality, the exposure ratios per municipality do not show a correlation to the areal size of municipality. Considering the spatial distribution of the exposure ratios per municipality, we identify a narrow area of high ratios from the southwestern to the northeastern of Switzerland, which coincide with the northern and pre-alpine regions of the Swiss Alps. Otherwise, low to medium ratios dominate, with the exception of some isolated high values.

Finally, Fig. 4 presents the exposure ratios per grid cell with the same thresholds of the five classes as in Fig. 3. Compared with Fig. 3 (municipalities) an equivalent spatial distribution of the exposure ratios appears in Fig. 4 (grids). As in the case of the exposure ratios per municipality, the exposure ratios per grid cell are generally higher in a broad strip that stretches from the southwest to the northeast. In

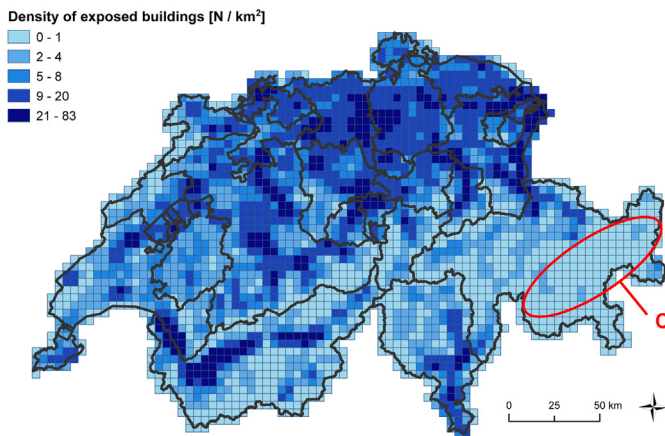


Fig. 2. Densities of flood exposed buildings in Switzerland per 4.23 × 4.23 km² grid cell, numbers per km². Thresholds of classes are identical to Fig. 1 (densities per municipalities). Fine lines represent grid cells and thick lines represent cantonal boundaries. Area C highlights an example, where the variability of exposure is more evident in density maps per grid cell than per municipality.

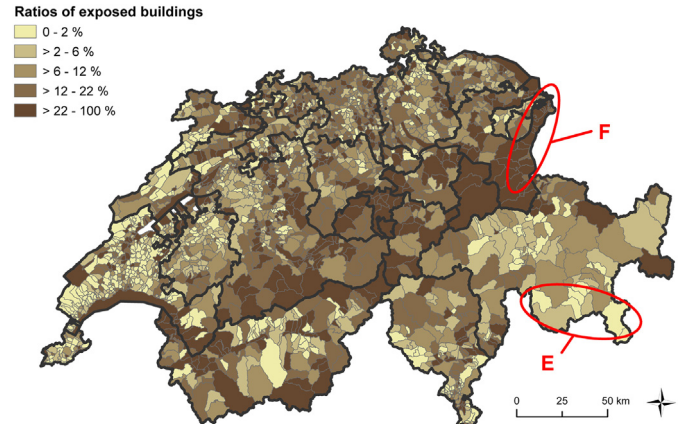


Fig. 3. Ratios of flood exposed buildings per Swiss municipality [numbers of exposed buildings/numbers of all buildings]. Data classes are (rounded) 20% quantiles. Fine lines represent municipal boundaries and thick lines represent cantonal boundaries. Area E highlights an example, where low values are observed in all four maps with 20% quantile representation (Figs. 1 to 4), and area F is characterized by high values in all four maps.

addition, we identify an accumulation of high values in the west (area D in Fig. 4), which does not appear in Fig. 3 (ratios per municipalities) due to the presence of some polygons without data. These polygons represent parts of lakes that are not assigned to municipalities and that do not contain buildings; thus, no exposure ratios are calculated. Finally, in the northern part of Switzerland, the map of exposure ratios per grid cells (Fig. 4) is easier to interpret than the map per municipalities (Fig. 3). This is mainly due to the smoothing effects caused by larger grids cells than municipalities and by the kernel density estimation procedure.

The prominent concentration of high exposure ratios in the narrow region that spans from the southwestern to the northeastern parts coincides with the northern and central parts of the Swiss Alps. This is a region that includes both concentrated settlements and wide areas characterized by relatively sparse populations. The main settlements here are concentrated in the few relatively flat areas, which are mainly floodplains, alluvial fans and debris cones.

When comparing exposure densities with exposure ratios (both sets of values organized per municipality or per grid cell), the extreme values (in the highest and the lowest classes) are found to be largely complementary. There are only a few major areas that are consistent.

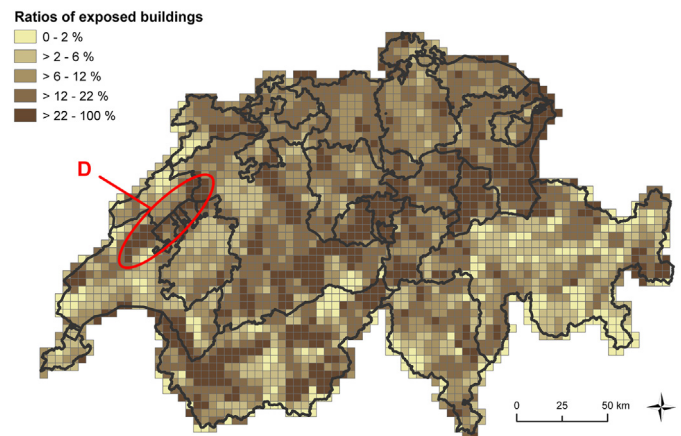


Fig. 4. Ratios of flood exposed buildings in Switzerland per 4.23 × 4.23 km² grid cell [numbers of exposed buildings/numbers of all buildings]. Thresholds of classes are identical to Fig. 3 (ratios per municipalities). Fine lines represent grid cells and thick lines represent lines cantonal boundaries. Area D highlights an accumulation of high values, which does not appear in Fig. 3 (ratios per municipalities).

Two examples are highlighted in Fig. 3: Area E is a region where low values are observed in all four maps (Figs. 1 to 4, see for a better overview Fig. A1 in Appendix) and area F is characterized by high values in all four maps. Overall, areas with high values in all four maps correspond with the relatively wide valleys of the main rivers connecting the high alpine regions with the foothills of the Alps, in particular, the Rhine river valley upstream of Lake Constanze (area F in Fig. 3) and the Rhone valley upstream of Lake Geneva (area A in Fig. 1). Both are considered to be densely populated areas surrounded by rather sparsely populated mountain areas. The large region of low values in the south-east observed in all four maps (Fig. A1 in Appendix) is almost congruent with the territory of Canton Graubünden. Authorities of Canton Graubünden pioneered the consideration of natural hazard aspects in the spatial planning processes in Switzerland. Legally binding hazard maps were introduced as early as 1963.

The aforementioned statements regarding the numbers of buildings also generally apply to the results describing the areal building footprints, and to a lesser degree, to the inhabitants. To provide an overview of the spatial distributions, the appendix presents the aggregations of the numbers of buildings (Fig. A1), of the areal building footprints (Fig. A2), and of the number of inhabitants (Fig. A3).

3.3. Hotspots of flood exposure

The results of the hotspot analyses are summarized in Figs. 5 and 6. The dark colored areas in all of the maps represent clusters of high values, based on the $Gi^*(d)$ statistic (Getis and Ord, 1992, Ord and Getis, 1995) and on a 95% confidence level. Fig. 5 provides an overview of 30 maps based on the five distance bands d (applied on data aggregated on grid cells, see columns in Fig. 5) and on the six analyzed exposure indicators (rows in Fig. 5) aggregated per grid cells. The results show (Fig. 5) that an increasing distance band value results in larger and more generalized hotspots, but does hardly change the position of these areas. The 18 maps in Fig. 6 provide a comparable overview to the one presented in Fig. 5 and are based on the same six indicators (rows in Fig. 6), but aggregated per municipalities and based on three distance bands d (columns in Fig. 6). In contrast to the grid cell aggregation, the results of the municipality-based aggregation highlight that an increasing distance band not only changes the size and shape of hotspot areas but, also their position under some circumstances (e.g. in the central northern part in the first row in Fig. 6). Thus, due to the spatially more stable results obtained, the grid cell approach is considered to be more appropriate for hotspot analyses. In addition, we consider the

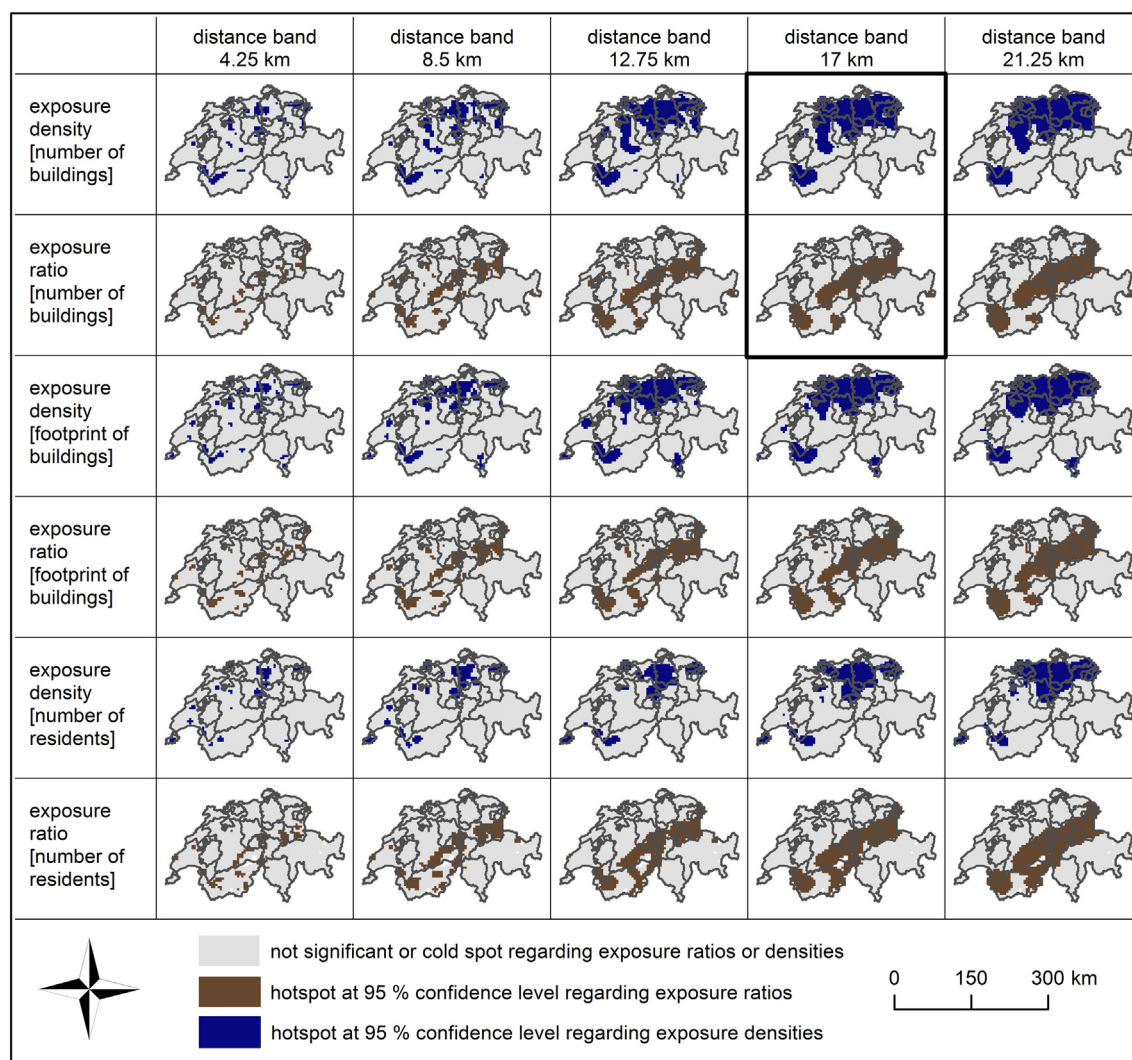


Fig. 5. Hotspots of flood exposure in Switzerland, based on data aggregated on $4.23 \times 4.23 \text{ km}^2$ grid cells. The dark colored areas show statistically significant clusters of high values (see legend) based on the local spatial autocorrelation statistic $Gi^*(d)$ by Getis and Ord (references see text), for five different fixed distance bands (columns) and six different types of indicators (rows). Confidence level at 95%, correction of false discovery rate applied. Details on the applied method described in Section 2.5. The two maps, which are replicated in Fig. 7, are highlighted by a bold frame. Gray lines represent cantonal boundaries.

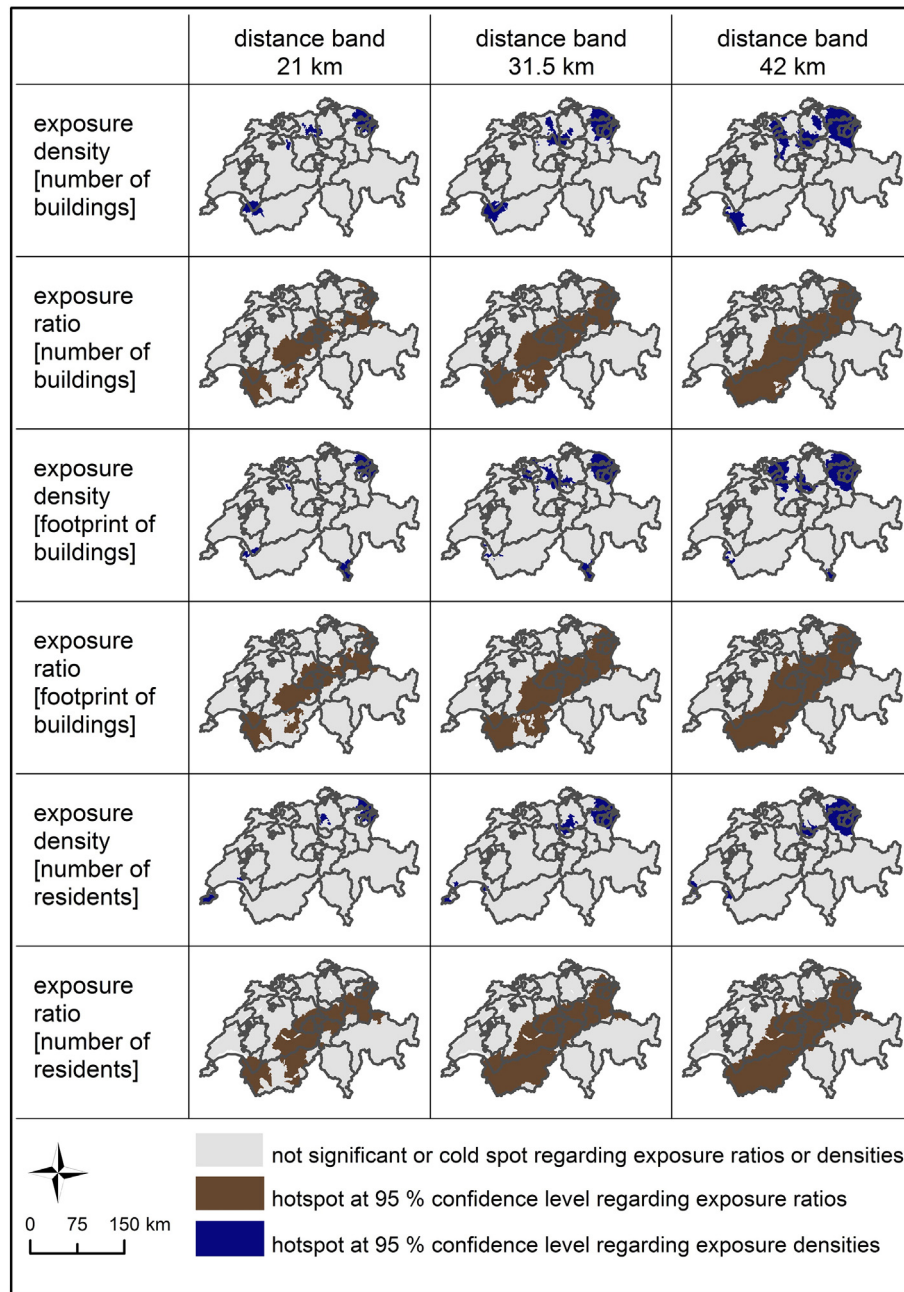


Fig. 6. Hotspots of flood exposure in Switzerland, based on data aggregated on municipalities. The dark colored areas show statistically significant clusters of high values (see legend) according to local spatial autocorrelation statistic $G_i^*(d)$ by Getis and Ord (references see text), for three different fixed distance bands (columns) and six different types of indicators (rows) Confidence level at 95%, correction of false discovery rate applied. Details on the applied method described in Section 2.5. Gray lines represent cantonal boundaries. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

analyses based on grid cells as 'spatially more consistent' in the sense that the sizes of the cells are all identical. Consequently, the size factor does not influence the result the way that variable sizes of municipalities do. For instance, the high exposure ratio (numbers of buildings) in the most eastern municipality of Switzerland is not identified as a part of a cluster (see first row with brown colored maps in Fig. 6), simply because this municipality is comparably large and has no neighboring municipalities with high exposure ratios (see Fig. 3). If the underlying data of the same municipality are aggregated on smaller areal units (e.g. grid cells of approximately 18 km^2), the same hotspot analysis shows significant clusters of high exposure ratios (see first row with brown colored maps in Fig. 5). While the reason that data aggregation on grid cell is to prefer over the aggregation based on administrative boundaries is generally valid, the optimal size of the distance band d is dependent on the

purpose of the spatial cluster analysis. It represents a compromise between producing continuous areas (by increasing d) and maintaining spatial differentiations (by decreasing d). Based on the evaluation of the parameters, we consider hotspot analyses based on grid cells and with a distance band of 17 km (second last column in Fig. 5). The selected parameters are optimal for providing a nationwide overview. Further analysis follows this optimal approach.

Fig. 7 presents hotspots of the number of exposed buildings, based on data aggregated on $4.23 \text{ km} \times 4.23 \text{ km}$ grid cells and with a distance band of 17 km. It can be observed that the hotspots based on density values are highly complementary to the hotspots based on exposure ratios. While the hotspots based on density values are mainly located in the northern part of Switzerland (with some additional spots in the southwest), the majority of the ones based on exposure ratios are

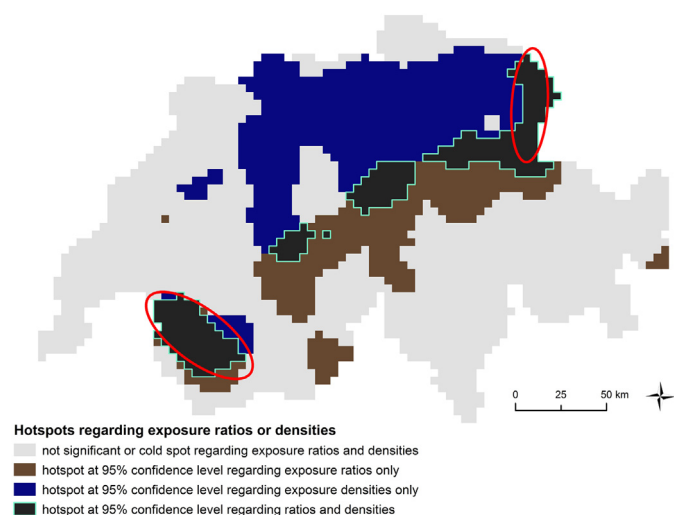


Fig. 7. (Selection and intersection of the two highlighted maps in Fig. 5): Hotspots of numbers of flood exposed buildings in Switzerland, based on data aggregated on 4.23×4.23 km² grid cells. The dark colored areas show statistically significant clusters of high values (see legend) according to local spatial autocorrelation statistic $G_i^*(d)$ by Getis and Ord (references see text). Confidence level at 95%, fixed distance band at 17 km, correction of false discovery rate applied. Details on the applied method described in Section 2.5. Red ellipses highlight the location of two major flood protection project in Switzerland. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

located within a broad strip from the southwestern to the northeastern parts of the country. Additionally, there are two small and isolated hotspots of exposure ratios, one located in the west and another in the east. Dark gray colored areas in Fig. 7 are areas where hotspots based on exposure densities and hotspots based on exposure ratios overlap. These dark gray areas are comparatively small and limited to the intermediate zones between the high alpine regions and the foothills of the Alps.

The spatial distributions of hotspots based on building footprint or on inhabitants respectively are similar to the distribution of hotspots based on the number of buildings (see Figs. 5 and 6).

3.4. Relevance of the MAUP

Our results show that the MAUP is relevant. The aggregation scheme influences both groups of results, namely, the spatial aggregates (see Section 3.2) and the hotspots (see Section 3.3) of flood exposed assets.

In particular, the aggregation scheme does not influence the *general* spatial distributions of flood exposure densities or ratios with respect to spatial aggregates. They remain the same whether the data is aggregated based on municipality districts or regular grids. However, upon further detailed inspection, they differ due to the effects of smoothing and coarsening (see Section 3.2). These effects illustrate the scaling aspect of the MAUP. In relation to MAUP, there are two reasons why aggregation based on grid cells is considered to be more appropriate for nationwide analyses. Firstly, aggregation based on (regular) grid cells supports the comparability of different regions better than the aggregation based on (irregularly shaped and sized) municipalities. Secondly, in regions with (very) small municipal districts (e.g. in the northwestern parts or in the very south of Switzerland), the visualization of aggregated values based on grid cells provides a more usable overview of the situation at the presented scale.

The comparison of the respective hotspots based on the two different aggregation schemes shows that they differ not so much with regards to exposure ratios (brown colored maps in Figs. 5 and 6), but remarkably when looking at exposure densities (blue colored maps in Figs. 5 and 6). The two different aggregation schemes using similar numbers and average sizes of spatial units, result in different areas of

flood exposure hotspot densities in Switzerland. That is, the results of these hotspot analyses are inconsistent when applying the two aggregation schemes, which vary in border locations. In other words, it matters where the borders of the spatial units are drawn. Consequently, the MAUP, especially the zonation aspect, should not be neglected.

3.5. Prioritization in risk reduction and risk management strategies

The dark colored areas in all presented maps (i.e. in the maps with 20% quantiles and in the hotspots maps) address the initial question pertaining to where flood protection measures should be prioritized. The dark blue areas (of exposure densities) indicate priorities for strategies following the concept of utilitarianism (Mill, 2007), whereas the dark brown ones (of high exposure ratios) identify priority areas for strategies which comply with Rawls' concept of justice (Rawls, 1971). In risk management, utilitarianism requests prioritization of the most cost efficient measures. High cost efficiency in turn is linked to high density of exposed assets, which is represented by the dark blue areas in this study. In contrast to utilitarianism, Rawls' concept on justice is focused on the most vulnerable areas and people. Vulnerable means to have low capacity to cope with a disaster. In this study, we use the share of exposed assets as an indicator for vulnerability, represented by brown colors in our maps. The maps with 20% quantile representation (of exposure densities and ratios, Figs. A1 to A3) are limited to the single spatial units of data aggregation, which are municipal districts or grid cells in our study. However, flood protection measures are often more effective when covering more than a single municipal district or a grid cell of 4.23 by 4.23 km (Thaler et al., 2016). Consequently, for strategy prioritization, there is less interest in the high values of *single* spatial units and greater interest in *clusters* of high values, i.e. in hotspots. As hotspots represent statistically significant spatial clusters (in our case at 95% confidence level) of high values, they support an evidence-based prioritization of regions for protection measures. Hence, the dark colored areas in Fig. 7 suggest regions of national priority for protection measures.

Switzerland's flood risk management strategy is still mainly driven by the reaction after large damaging flood events (Suter et al., 2016). The same reaction was observed by Thielen et al. (2016) after the 2013 flood in Germany and also in other countries. However, the number of preventive risk reduction projects in Switzerland are increasing with an emphasis on areas, which our study identifies as hotspots based on exposure densities. This emphasis reflects a commonly recommended strategic focus on cost efficiency (Meyer et al., 2013; Mori and Perrings, 2012). It is implemented into the decision making process on the allocation of federal subsidies by a respective tool to provide evidence of cost efficient measures (Bründl et al., 2009). Only measures with evident cost efficiency are supported by national funds. Currently, there is increasing awareness about certain regions indicated in our study as the most vulnerable territories within Switzerland. However, the focus in these areas is on their capacity to cope with floods (and other natural hazards), rather than on the reduction of their exposure ratios. Thus, it would be beneficial to determine whether current risk management strategies e.g. intervention or risk transfer by extensive insurance systems (Gretener, 2011; von Ungern-Sternberg, 2004) in these vulnerable areas are sufficient in the case of the occurrence of an event (as discussed within the Austrian context by Holub and Fuchs, 2009).

Nevertheless, within Switzerland's strategic focus on cost efficiency, the most vulnerable regions identified in our study are not neglected. For instance, the federal authorities support precisely two current technical flood protection projects, with a dedicated contact person. These projects are the 'Alpenrhein Expansion Project' conducted on the river Rhine upstream of Lake Constance and the 'Third Rhone Correction' upstream of Lake Geneva (Federal Office for the Environment, 2016). These two projects are not only operating within identified hotspots based on density values, but also within hotspots based on exposure ratios. As a result, the aforementioned projects lay within the dark gray

colored areas in Fig. 7 (see red ellipses in Fig. 7) that indicate areas where the hotspots based on density values and on ratios overlap. This means that the prioritization of these two projects at the national level is in line with our insights. Our findings suggest that the prioritization of these regions of overlapping hotspots is required to support the realization of both types of strategies focused on cost efficiency and on the most vulnerable regions.

4. Conclusions and outlook

The preceding sections illustrate the utility and pitfalls of spatial statistics applied on flood exposure data in Switzerland. We show that the detection of hotspots, i.e. of statistically significant clusters of high values, is feasible at the national scale and based on the use of spatially explicit data. We find that spatial cluster analyses support the generation of more informative databases, which can be used to prioritize flood protection measures, especially compared with the limited information from 'simple' maps of spatially aggregated data represented in quantiles. However, the analysis results into more than one single answer to the question 'where are the hotspots of flood exposure?', at least in the case of Switzerland. Thus, the proposed analysis provides a broad basis for decisions on different types of prioritization strategies in flood risk management.

First of all, the answer depends on the type of the indicator. The results of our case study suggest largely complementary hotspots based on exposure densities and exposure ratios. This means that priority areas for protection measures following cost efficient strategies (utilitarianism) and for measures focusing on the most vulnerable regions (Rawls' concept on justice) hardly overlap in Switzerland. Identifying these differences on a national level could already be an important step towards evaluating prioritization strategies. The prioritization of cost efficient measures is a well-established strategy with respective tools and criteria supporting the decision process in Switzerland and elsewhere. The density of exposed assets is a key determinant of cost efficiency. In contrast, the focus on vulnerability is less common and the development of the respective concepts and tools is still at a very early stage. The term vulnerability is already subject to ongoing academic discussions (cf. Birkmann et al., 2013), even more diverse are the existing concepts of vulnerability assessments upon which flood management decisions are based. The exposure ratio, used in this study, is one of all conceivable criteria for vulnerability assessments.

Secondly, there may be differences in the answer when considering different kinds of assets. However, only minor differences between the results regarding the number or footprint or inhabitants of exposed buildings are identified in Switzerland. More importantly, the way data aggregation is conducted influences the results. That is, the MAUP is relevant and must not be neglected in any spatial cluster analysis based on aggregated flood exposure data. By presenting hotspots based on different distance bands, we further exemplify the influence of parameter settings on the results of a hotspot test statistic. Not only the parameter setting influence the identification of spatial clusters, but already the type of the test statistic that is applied does. In future studies, it might be interesting to apply other spatially explicit local statistics and to compare them with the presented approaches, e.g. procedures presented by Aldstadt and Getis (2006), Anselin (1995) or Tango and Takahashi (2005). Data aggregation based on small catchment areas (instead of grid cells or municipalities), combined with the use of connectivity indices (instead of Euclidean distance) as the neighborhood criteria, would be another promising approach for future improvements.

Regardless of the data and the methods used, it is essential to select them based on the questions to be answered for flood risk management. Furthermore, we emphasize the utility of publishing hotspots of flood exposure in combination with notes on their dependency on the parameters of the applied method. This way, flood exposure hotspot analyses

provide added value to evidence-based decisions making pertaining to the prioritization of flood risk reduction measures.

Supplementary data to this article can be found online at <http://dx.doi.org/10.1016/j.scitotenv.2017.03.216>.

Acknowledgments

Funding from the Swiss Mobiliar ('die Mobiliar AG') supported the completion of this research. We thank the natural hazards group at the Swiss Mobiliar for acquiring and compiling the communal flood hazard maps; Candace Chow for editorial assistance; Sven Fuchs for proofreading and Markus Mosimann for his support with the design of the figures. We like to thank the anonymous reviewer and the editor for their inputs which substantially improved this manuscript.

References

- Aldstadt, Jared, Getis, Arthur, 2006. Using AMOEBA to create a spatial weights matrix and identify spatial clusters. *Geogr. Anal.* 38 (4):327–343. <http://dx.doi.org/10.1111/j.1538-4632.2006.00689.x>.
- Anselin, Luc, 1995. Local indicators of spatial association - LISA. *Geogr. Anal.* Vol 27 (2), 93–115.
- Aubrecht, Christoph, Fuchs, Sven, Neuhold, Clemens, 2013. Spatio-temporal aspects and dimensions in integrated disaster risk management. *Nat. Hazards* 68 (3): 1205–1216. <http://dx.doi.org/10.1007/s11069-013-0619-9>.
- Birkmann, Jörn, Cardona, Omar D., Carreño, Martha L., Barbat, Alex H., Pelling, Mark, Schneiderbauer, Stefan, et al., 2013. Framing vulnerability, risk and societal responses. The MOVE framework. *Nat. Hazards* 67 (2):193–211. <http://dx.doi.org/10.1007/s11069-013-0558-5>.
- Black, Andrew R., Burns, John C., 2002. Re-assessing the flood risk in Scotland. *Sci. Total Environ.* 294 (1–3):169–184. [http://dx.doi.org/10.1016/S0048-9697\(02\)00062-1](http://dx.doi.org/10.1016/S0048-9697(02)00062-1).
- Borden, Kevin A., Cutter, Susan L., 2008. Spatial patterns of natural hazards mortality in the United States. *Int. J. Health Geogr.* 7:64. <http://dx.doi.org/10.1186/1476-072X-7-64>.
- Bortner, Patricia, 1999. Risikoanalyse bei gravitativen Naturgefahren. Methode. Edited by Bundesamt für Umwelt, Wald und Landschaft (BUWAL) (Umwelt-Materialien, Nr. 107/I). Available online at: <http://www.bafu.admin.ch/publikationen/publikation/00131/index.html?lang=de> (checked on 7/21/2016).
- Bründl, Michael, Romang, Hans E., Bischof, Nicole, Rheinberger, Christoph M., 2009. The risk concept and its application in natural hazard risk management in Switzerland. *Nat. Hazards Earth Syst. Sci.* 9, 801–813.
- Bundesamt für Umwelt BAFU, 2016a. Von der Risikoanalyse zur Massnahmenplanung. Arbeitsgrundlage für Hochwasserschutzprojekte Bern (Umweltwissen, 1606).
- Bundesamt für Umwelt BAFU, 2016b. Umgang mit Naturgefahren in der Schweiz - Bericht des Bundesrates.
- Caldas de Castro, Marcia, Singer, Burton H., 2006. Controlling the false discovery rate: a new application to account for multiple and dependent tests in local statistics of spatial association. *Geogr. Anal.* 38, 180–208.
- Cammerer, Holger, Thieken, Annegret H., Verbürg, Peter H., 2013. Spatio-temporal dynamics in the flood exposure due to land use changes in the Alpine Lech Valley in Tyrol (Austria). *Nat. Hazards* 68 (3):1243–1270. <http://dx.doi.org/10.1007/s11069-012-0280-8>.
- Charlton, Martin, 2008. Modifiable areal unit problem (MAUP). In: Kemp, Karen K. (Ed.), *Encyclopedia of Geographic Information Science*. SAGE Publications, Inc., pp. 289–290.
- Chen, Lixia, van Westen, Cees J., Hussin, Haydar, Ciurean, Roxana L., Turkington, Thea, Chavarro-Rincon, Diana, Shrestha, Dhruva P., 2016. Integrating expert opinion with modelling for quantitative multi-hazard risk assessment in the Eastern Italian Alps. *Geomorphology* 273:150–167. <http://dx.doi.org/10.1016/j.geomorph.2016.07.041>.
- de Moel, Hans, Aerts, Jeroen C.J.H., Koomen, Eric, 2011. Development of flood exposure in the Netherlands during the 20th and 21st century. *Glob. Environ. Chang.* 21 (2): 620–627. <http://dx.doi.org/10.1016/j.gloenvcha.2010.12.005>.
- de Moel, Hans, Jongman, Brenden, Kreibich, Heidi, Merz, Bruno, Penning-Rowsell, Edmund, Ward, Philip J., 2015. Flood risk assessments at different spatial scales. *Mitig. Adapt. Strateg. Glob. Chang.* 20 (6):865–890. <http://dx.doi.org/10.1007/s11027-015-9654-z>.
- European Parliament, 2007. Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risk. 2007/69/EC. Off. J. Eur. Union 288, 27–34.
- Federal Office for the Environment FOEN, 2008. Terms of Use Aquaprotect. Available online at: <http://www.bafu.admin.ch/naturgefahren/14186/14801/16598/16600/index.html?lang=en> (checked on 9/26/2016).
- Federal Office for the Environment FOEN, 2016. Flood Protection Section. Responsibilities of Staff. Available online at: <http://www.bafu.admin.ch/org/organisation/00180/00188/index.html?lang=en> (checked on 10/2/2016).
- Federal Statistical Office FSO, 2016. Buildings and Dwellings Statistic (Since 2009). Factsheet - Surveys, Sources. Neuchâtel. Available online at: <https://www.bfs.admin.ch/bfs/en/home/statistics/construction-housing/surveys/gws2009.html> (checked on 1/9/2017).
- Feyen, Hans, Mehlhorn, Jens, Menzinger, Ivo, 2003. Invention: Method for Evaluating Flood Plain Risks (Patent Application in the United States Patent and Trademark Office).

- Figueiredo, Rui, Martina, Mario L.V., 2016. Using open building data in the development of exposure data sets for catastrophe risk modelling. *Nat. Hazards Earth Syst. Sci.* 16 (2): 417–429. <http://dx.doi.org/10.5194/nhess-16-417-2016>.
- Fuchs, Sven, Keiler, Margreth, Sokratov, Sergey, Shnyarkov, Alexander, 2013. Spatiotemporal dynamics. The need for an innovative approach in mountain hazard risk management. *Nat. Hazards* 68 (3):1217–1241. <http://dx.doi.org/10.1007/s11069-012-0508-7>.
- Fuchs, Sven, Keiler, Margreth, Zischg, Andreas P., 2015. A spatiotemporal multi-hazard exposure assessment based on property data. *Nat. Hazards Earth Syst. Sci.* 15 (9): 2127–2142. <http://dx.doi.org/10.5194/nhess-15-2127-2015>.
- Fuchs, Sven, Orntsmüller, Christine, Totschnig, Reinhold, 2012. Spatial scan statistics in vulnerability assessment. An application to mountain hazards. *Nat. Hazards* 64 (3): 2129–2151. <http://dx.doi.org/10.1007/s11069-011-0081-5>.
- Fuchs, Sven, Röthlisberger, Veronika, Thaler, Thomas, Zischg, Andreas P., Keiler, Margreth, 2017. Natural hazard management from a co-evolutionary perspective: exposure and policy response in the European Alps. *Ann. Am. Assoc. Geogr.* 107 (2).
- Getis, Arthur, Ord, John K., 1992. The analysis of spatial association by use of distance statistics. *Geogr. Anal.* Vol. 24 (3), 189–206.
- Getis, Arthur, 2008. A history of the concept of spatial autocorrelation: a geographer's perspective. *Geogr. Anal.* 40, 297–309.
- Gretenner, Max, 2011. Die Versicherung von Elementarschäden durch die privaten Sachversicherer in der Schweiz. Schweizerischer Versicherungsverband, Zürich Available online at: <http://www.svv.ch/de/publikationen/die-versicherung-von-elementarschaeden-durch-die-privaten-sachversicherer-der-schweiz> (checked on 8/22/2014).
- Hallegatte, Stephane, Green, Colin, Nicholls, Robert J., Corfee-Morlot, Jan, 2013. Future flood losses in major coastal cities. *Nat. Clim. Chang.* 3 (9):802–806. <http://dx.doi.org/10.1038/nclimate1979>.
- Holub, Markus, Fuchs, Sven, 2009. Mitigating mountain hazards in Austria – legislation, risk transfer, and awareness building. *Nat. Hazards Earth Syst. Sci.* 9 (2):523–537. <http://dx.doi.org/10.5194/nhess-9-523-2009>.
- Huttenlau, Matthias, Stötter, Johann, Stiefelmeyer, Heinz, 2010. Risk-based damage potential and loss estimation of extreme flooding scenarios in the Austrian Federal Province of Tyrol. *Nat. Hazards Earth Syst. Sci.* 10 (12):2451–2473. <http://dx.doi.org/10.5194/nhess-10-2451-2010>.
- IPCC, 2012. Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. With assistance of Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, P.M. Midgley. IPCC. Cambridge University Press, Cambridge, UK and New York, NY, USA.
- Johnson, Clare, Penning-Rowsell, Edmund, Parker, Denis, 2007. Natural and imposed injustices: the challenges in implementing 'fair' flood risk management policy in England. *Geogr. J.* 173:374–390 <http://www.jstor.org/stable/30130632>.
- Jongman, Brenden, Hochrainer-Stigler, Stefan, Feyen, Luc, Aerts, Jeroen C.J.H., Mechler, Reinhard, Botzen, Wouter W.J., et al., 2014. Increasing stress on disaster-risk finance due to large floods. *Nat. Clim. Chang.* 4 (4):264–268 Available online at: <http://www.nature.com/nclimate/journal/v4/n4/full/nclimate2124.html> (checked on 7/2/2014).
- Jongman, Brenden, Ward, Philip J., Aerts, Jeroen C.J.H., 2012. Global exposure to river and coastal flooding. Long term trends and changes. *Glob. Environ. Chang.* 22 (4): 823–835. <http://dx.doi.org/10.1016/j.gloenvcha.2012.07.004>.
- Jonkman, Bas S.N., Bočkarjova, Marija, Kok, Matthijs, Bernardini, Patrizia, 2008. Integrated hydrodynamic and economic modelling of flood damage in the Netherlands. *Ecol. Econ.* 66 (1):77–90. <http://dx.doi.org/10.1016/j.ecolecon.2007.12.022>.
- Kazakis, Nerantzis, Kougias, Ioannis, Patsialis, Thomas, 2015. Assessment of flood hazard areas at a regional scale using an index-based approach and Analytical Hierarchy Process: application in Rhodope-Evros region, Greece. *Sci. Total Environ.* 538:555–563. <http://dx.doi.org/10.1016/j.scitotenv.2015.08.055>.
- Klijn, Frans, Kreibich, Heidi, de Moel, Hans, Penning-Rowsell, Edmund, 2015. Adaptive flood risk management planning based on a comprehensive flood risk conceptualisation. *Mitig. Adapt. Strateg. Glob. Chang.* 20 (6):845–864. <http://dx.doi.org/10.1007/s11027-015-9638-z>.
- Knox, E. George, 1989. Detection of clusters. In: Elliott, Paul (Ed.), *Methodology of Enquiries Into Disease Clustering*, pp. 17–22 Workshop. Papers and discussions. (London).
- Legendre, Pierre, Legendre, Louis, 2012. *Numerical Ecology*. 3rd English ed. Elsevier, Amsterdam (Chapters 8 and 13).
- Levine, Ned, 2008. CrimeStat: a spatial statistical program for the analysis of crime incidents. In: Shekhar, Shashi, Xiong, Hui (Eds.), *Encyclopedia of GIS*. Springer, New York, pp. 187–193.
- Loat, Roberto, Petrascheck, Armin, 1997. Consideration of Flood Hazards for Activities with Spatial Impact. Edited by Bundesamt für Wasserwirtschaft (BWV) Federal Office for Water Management, Bundesamt für Raumplanung (BRP) Federal Office for Spatial Planning, Bundesamt für Umwelt, Wald und Landschaft (BUWAL) Federal Office for the Environment, Forests and Landscape. Biel. Available online at: <http://www.bafu.admin.ch/publikationen/publikation/00786/index.html?lang=en> (checked on 7/21/2016).
- Lugeri, Nicola, Kundzewicz, Zbigniew W., Genovese, Elisabetta, Hochrainer, Stefan, Radziejewski, Maciej, 2010. River flood risk and adaptation in Europe—assessment of the present status. *Mitig. Adapt. Strateg. Glob. Chang.* 15 (7):621–639. <http://dx.doi.org/10.1007/s11027-009-9211-8>.
- Lung, Tobias, Laval, Carlo, Hiederer, Roland, Dosio, Alessandro, Bouwer, Laurens M., 2013. A multi-hazard regional level impact assessment for Europe combining indicators of climatic and non-climatic change. *Glob. Environ. Chang.* 23 (2):522–536. <http://dx.doi.org/10.1016/j.gloenvcha.2012.11.009>.
- Mazzorana, Bruno, Levaggi, Laura, Keiler, Margreth, Fuchs, Sven, 2012. Towards dynamics in flood risk assessment. *Nat. Hazards Earth Syst. Sci.* 12 (11):3571–3587. <http://dx.doi.org/10.5194/nhess-12-3571-2012>.
- Merz, Bruno, 2006. *Hochwasserrisiken: Grenze und Möglichkeiten der Risikoabschätzung*. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart.
- Merz, Bruno, Thieken, Annegret H., 2004. Flood risk analysis: concepts and challenges. *Österreichische Wasser- und Abfallwirtschaft* 56 (3–4), 27–34.
- Meyer, Volker, Becker, Nina, Markantonis, Vasileios, Schwarze, Reimund, van den Bergh, Jeroen C.J.M., Bouwer, Laurens M., et al., 2013. Review article: assessing the costs of natural hazards – state of the art and knowledge gaps. *Nat. Hazards Earth Syst. Sci.* 13 (5):1351–1373. <http://dx.doi.org/10.5194/nhess-13-1351-2013>.
- Mill, John Stuart, 2007. *Utilitarianism, Liberty and Representative Government*. Wildside Press.
- Mori, Koichiro, Perrings, Charles, 2012. Optimal management of the flood risks of flood-plain development. *Sci. Total Environ.* 431:109–121. <http://dx.doi.org/10.1016/j.scitotenv.2012.04.076>.
- Muis, Sanne, Guneralp, Burak, Jongman, Brenden, Aerts, Jeroen C.J.H., Ward, Philip J., 2015. Flood risk and adaptation strategies under climate change and urban expansion: a probabilistic analysis using global data. *Sci. Total Environ.* 538:445–457. <http://dx.doi.org/10.1016/j.scitotenv.2015.08.068>.
- Openshaw, Stan, 1984. The Modifiable Areal Unit Problem. *Geo Abstracts Univ. of East Anglia, Norwich (Catmog: concepts and techniques in modern geography)*.
- Ord, John K., Getis, Arthur, 1995. Local spatial autocorrelation statistics: distributional issues and an application. *Geogr. Anal.* Vol. 27 (4), 286–306.
- Papathoma-Köhle, Maria, Kappes, Melanie, Keiler, Margreth, Glade, Thomas, 2011. Physical vulnerability assessment for alpine hazards: state of the art and future needs. *Nat. Hazards* 58 (2):645–680. <http://dx.doi.org/10.1007/s11069-010-9632-4>.
- PLANAT, 2005. *Protection Against Natural Hazards in Switzerland - Vision and Strategy (Executive Summary)*.
- Rawls, John, 1971. *A theory of justice*. Harvard University Press, Cambridge.
- Rojas, Rodrigo, Feyen, Luc, Watkiss, Paul, 2013. Climate change and river floods in the European Union. Socio-economic consequences and the costs and benefits of adaptation. *Glob. Environ. Chang.* 23 (6):1737–1751. <http://dx.doi.org/10.1016/j.gloenvcha.2013.08.006>.
- Silverman, Bernard W., 1986. *Density Estimation for Statistics and Data Analysis*. Chapman and Hall, New York, p. 76 (Monographs on statistics and data analysis). (equation 4.5).
- Snow, John, 1855. *On the Mode of Communication of Cholera*. second ed. Churchill, London.
- Staffler, Hanspeter, Pollinger, Rudolf, Zischg, Andreas P., 2008. In: *Interpraevent (Ed.), Prioritisation in the planning of permanent protection structures against floods and debris flows on the regional scale in the autonomous province of Bolzano - South Tyrol*, pp. 323–334 Conference Proceedings.
- Su, Wei, Zhang, Xiaodong, Wang, Zhen, Su, Xiaohui, Huang, Jianxi, Yang, Siqian, Liu, Sanchao, 2011. Analyzing disaster-forming environments and the spatial distribution of flood disasters and snow disasters that occurred in China from 1949 to 2000. *Math. Comput. Model.* 54 (3–4):1069–1078. <http://dx.doi.org/10.1016/j.mcm.2010.11.037>.
- Suter, Hannes, Thomi, Luzius, Kern, Raoul, Künzler, Matthias, Gusterer, Conny, Zischg, Andreas P., et al., 2016. What makes a successful flood control project? An evaluation of project procedure and risk based on the perspective of Swiss communes. In: *Koboltschnig, Gernot (Ed.), Interpraevent 2016. Living With Natural Risks. Proceedings of the 13th Congress*. Lucerne, pp. 159–167.
- swisstopo, 2016a. *swissTLM3D, The Topographic Landscape Model TLM (of Switzerland) Version 1.x as per March 2016*. (Description and acquisition online at, checked on 9/27/2016).
- swisstopo, 2016b. *Objektkatalog swissTLM3D 1.4*. Available online at: https://www.swisstopo.admin.ch/content/swisstopo-internet/de/home/products/landscape/tlm3d/_jcr_content/contentPar/tabs/items/dokumente/tabPar/downloadlist/downloadItems/759_1464676126625.download/201603swisstlm3d14okd.pdf (checked on 7/20/2016).
- swisstopo, 2016c. *swissTLM3D Nachführungsinfo 2016*. Available online at: https://www.swisstopo.admin.ch/content/swisstopo-internet/de/home/products/landscape/tlm3d/_jcr_content/contentPar/tabs/items/dokumente/tabPar/downloadlist_159209046/downloadItems/760_1464676201314.download/swisstlm3drelease2016dedefbarrierefrei.pdf (checked on 7/20/2016).
- swisstopo, 2016d. *swissBOUNDARIES3D. Grenzen Schweizweit 3D*. Available online at: https://www.swisstopo.admin.ch/content/swisstopo-internet/de/home/products/landscape/boundaries3d/_jcr_content/contentPar/tabs/items/dokumente/tabPar/downloadlist/downloadItems/793_1464683261852.download/2016023boundinfodbarrierefrei.pdf (checked on 8/4/2016).
- Tango, Toshiro, Takahashi, Kunihiro, 2005. A flexibly shaped spatial scan statistic for detecting clusters. *Int. J. Health Geogr.* 4:11. <http://dx.doi.org/10.1186/1476-072X-4-11>.
- Thaler, Thomas A., Priest, Sally J., Fuchs, Sven, 2016. Evolving inter-regional co-operation in flood risk management. Distances and types of partnership approaches in Austria. *Reg. Environ. Chang.* 16 (3):841–853. <http://dx.doi.org/10.1007/s10113-015-0796-z>.
- Thieken, Annegret H., Kienzler, Sarah, Kreibich, Heidi, Kuhlicke, Christian, Kunz, Michael, Mühr, Bernhard, et al., 2016. Review of the flood risk management system in Germany after the major flood in 2013. *E&S* 21 (2). <http://dx.doi.org/10.5751/ES-08547-210251>.
- UNISDR, 2015a. *Global Assessment Report on Disaster Risk Reduction. Making Development Sustainable: The Future of Disaster Risk Management*. Geneva, Switzerland.
- UNISDR, 2015b. *Sendai Framework for Disaster Risk Reduction 2015–2030*. Geneva, Switzerland.
- Url, Thomas, Sinabell, Franz, 2008. Flood risk exposure in Austria - options for bearing risk efficiently. *Schmollers Jahrbuch*. vol. 128, pp. 593–614.

- van der Veen, Anne, Logtmeijer, Christian, 2005. **Economic hotspots: visualizing vulnerability to flooding.** *Nat. Hazards* 36, 65–80.
- Visser, Hans, Petersen, Arthur C., Ligtoet, Willem, 2014. On the relation between weather-related disaster impacts, vulnerability and climate change. *Clim. Chang.* 125 (3–4): 461–477. <http://dx.doi.org/10.1007/s10584-014-1179-z>.
- von Ungern-Sternberg, Thomas, 2004. *Efficient Monopolies. The Limits of Competition in the European Property Insurance Market.* Oxford University Press, New York.
- Winsemius, Hessel C., Aerts, Jeroen C.J.H., van Beek, Ludovicus P.H., Bierkens, Marc F.P., Bouwman, Arno, Jongman, Brenden, et al., 2016. Global drivers of future river flood risk. *Nat. Clim. Chang.* 6 (4):381–385. <http://dx.doi.org/10.1038/nclimate2893>.
- Zimmermann, Markus, Keiler, Margreth, 2015. International frameworks for disaster risk reduction. Useful guidance for sustainable mountain development? *Mt. Res. Dev.* 35 (2):195–202. <http://dx.doi.org/10.1659/MRD-JOURNAL-D-15-00006.1>.
- Zischg, Andreas P., Schober, Stephan, Sereinig, Norbert, Rauter, Marina, Seymann, Christof, Goldschmidt, Franz, et al., 2013. Monitoring the temporal development of natural hazard risks as a basis indicator for climate change adaptation. *Nat. Hazards* 67 (3):1045–1058. <http://dx.doi.org/10.1007/s11069-011-9927-0>.